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INTERMEDIATE ENERGY PROTON AND LIGHT-ION SCATTERING

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A review is presented of recent (1979-81) developments in the field of intermediate-energy proton and light-ion scattering from nuclei. New theoretical and calculational techniques of particular interest to experimentalists are discussed. Emphasis is placed on topics in nuclear structure physics - giant resonances, pion-condensation precursor phenomena, and polarization transfer (spin-flip) experiments - where intermediate energy proton and light-ion scattering has made new and unique contributions.

1. Introduction

The general features of high-energy proton scattering in the study of nuclear-structure physics have been emphasized in several ICOHEPANS talks in the past[1], hence I will concentrate on the new developments in this subfield, particularly those that have appeared since the 1979 Vancouver Conference. This list (table 1) appears as a collection of disparate subjects

Table I - Outline of Subjects Covered

1. Introduction
2. N-N Interaction and Recent Theoretical Developments
   - N-N Interaction
   - DWIA description of inelastic scattering
   - Data-to-data analyses
3. Nuclear Structure and Reaction
   - Giant Resonances
   - Delta-isobar-hole configurations
   - Pion-condensation precursors
   - Measurement of the Q parameter
   - Spin-flip measurements
4. Summary

having no central unifying theme. Although there is some underlying unity not apparent in the titles, the first impression is essentially correct. After all, proton and light-ion scattering is a tool which allows us to investigate certain properties of nuclei and nuclear interactions, not an end in itself. A very important point, moreover, which has been emphasized recently,[2] is that the most effective use of this tool is often in conjunction with other tools, specifically the scattering of mesonic and electromagnetic probes, in the pursuit of a common goal in nuclear structure physics.

A notable absence in the list in table I is the subject of neutron radii. This omission reflects my view that the field of elastic scattering is now at the stage of asking, "Just how reliable are these calculations, anyway?"[3] It also reflects my predjudice that neutron radii have been talked abcut enough recently.[4]

2. The N-N Interaction and Recent Theoretical Developments

Fundamental to the use of proton and light-ion scattering as a probe of nuclear structure are the theories employed to describe the reaction. The foundations of the commonly used multiple scattering theories were laid down over 20 years ago.[5] New developments continue to occur and have been reviewed recently.[6] In this section I will discuss a few developments from an experimentalist's point of view, which are very important in terms of understanding and interpreting experimental data.

A crucial ingredient in the theoretical discription of nucleon scattering at high energies is an accurate knowledge of the free N-N interaction. Phase-shift analyses for energies at and below 500 MeV have been available for some time. Recently the data base from 500 MeV to 800 MeV has been considerably augmented,[7] with the result that phase-shift analyses with considerably fewer ambiguities are now available in this range.[8] It should be emphasized, however, that even for energies where the phase shifts are "well-known", the N-N scattering amplitudes may not be very well determined in the range of momentum transfer where most N-nucleus experiments are performed.

Of considerable importance are theoretical and calculational developments which aid experimentalists in planning experiments and in understanding their data. I will discuss two such developments; the work of Love and Franey[9] who have constructed a general distorted-wave impulse approximation (DWIA) code for inelastic scattering, and the work of the Penn group[10] who have formulated a simple and elegant "data-to-data" version of multiple-scattering theory.

Figure 1 shows schematically the procedure employed for DWIA calculations. The crucial step is to represent the N-N scattering amplitudes in terms of a sum of Yukawa potentials which can then be used in anti-symmetrized coordinate-space DWIA calculations employing nearly any set of wave functions one desires to test. Such calculations include effects from all the terms in the q-space N-N scattering amplitudes.

Since the work of Love and Franey one has a more global view of the energy dependence of the various pieces of the N-N interaction. Figure 2 shows the energy dependence of the strengths of the four spin and isospin dependent pieces of the central interaction at q = 0. It is immediately clear that in the range near E_p = 800 MeV scalar-isoscalar transitions will predominate, while the range from 200 to 400 MeV is optimum for the study of spin-flip transitions with minimum interference from scalar-isoscalar reactions.

The validity of the DWIA for hadrons becomes more dubious the lower the beam energy. For protons, the range E_p = 150 MeV might seem too low, and indeed there have been some notable failures of the DWIA here.[11,12] An approach that seems very promising at lower energies is a simple correction of the effective N-N interaction in the form of a density dependence which is taken from the local density approximation.[12] The improvement in the quality of fits to both cross sections and analyzing powers is remarkable for the isoscalar transitions to which this correction has been applied.

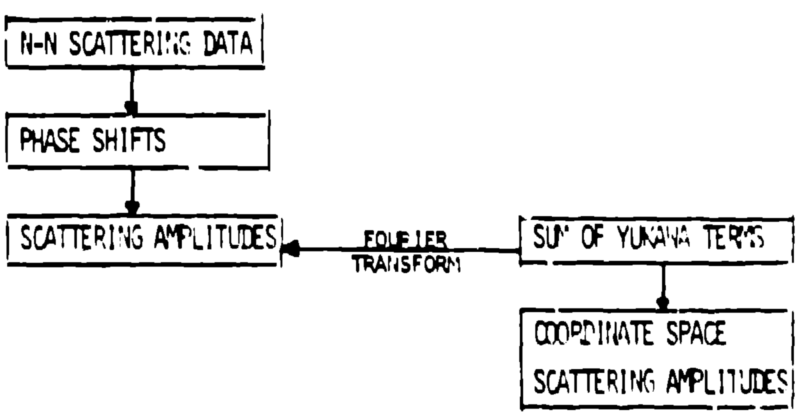


Fig. 1 Schematic procedure for obtaining coordinate space scattering anmplitudes for use in DWIA calculations. The crucial step is a fit of Fourier-transformed Yukawa terms to the q-space N-N scattering amplitudes.

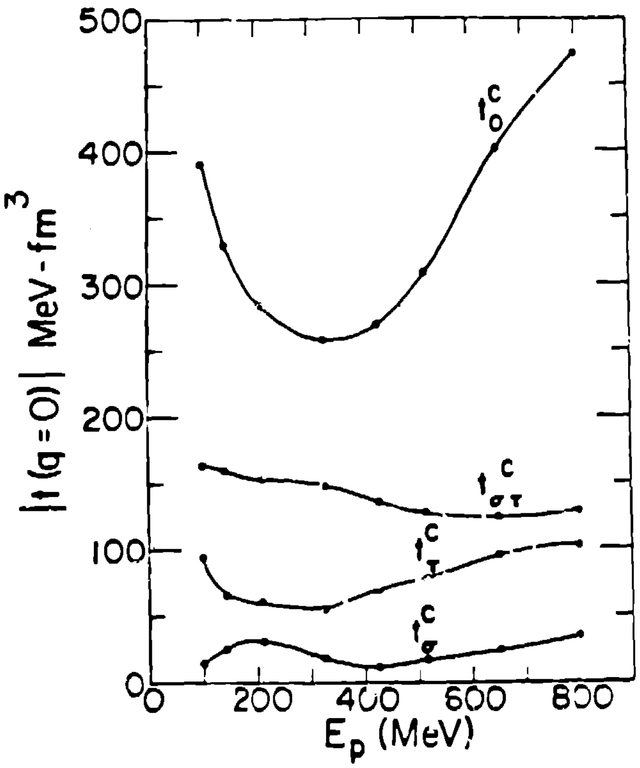


Fig. 2 Energy dependence of the N-N t matrix at q=0 for various spin and isospin channels.

Finally on the subject of theoretical developments I want to mention the work of Amado, Lenz, McNeil, and Sparrow (ALMS)[10] who have derived a set of very simple "data-data" relations, and who have, in the process, considerably clarified the physics of elastic scattering and inelastic scattering to collective states at intermediate energies. Starting from the eikonal N-nucleus scattering amplitude and employing the Tassie model for transition densities, ALMS are able to show that the cross section for inelastic scattering to a state of spin L (natural parity) is given by

$$(d\sigma/d\Omega)_L = \left[\frac{4\pi}{3Z}\right]^2 \frac{B(EL)}{c^{2L}}\, q^2 c^2\, (d\sigma/d\Omega)_{EL.}(\theta+\delta\theta)\, e^{2\pi a k \delta\theta}$$

with

$$\delta\theta = \frac{(L-1)\phi}{kc} \qquad \text{for L odd}$$

$$\delta\theta = \frac{(L-1)\phi + \pi/2}{kc} \qquad \text{for L even}$$

and $\phi = \tan^{-1}(\pi a/c)$

where a and c are respectively the diffuseness and half-density radius of a Fermi distribution. The remarkable feature of this equation is that it bypasses the theoretical description of elastic scattering usually required for inelastic scattering - only experimental data are used. As ALMS have pointed out, the data-to-data feature has the effect of removing some of the inaccuracies present in the orginal theory. For example, imperfect optical model fits result in imperfect inelastic cross section predictions.

This model has been extended to describe polarization observables as well as cross sections. It is clear from the excellent agreement obtained with experimental analyzing power (Fig. 3) that this observable contributes no new nuclear structure information for most natural parity transitions at high energies.

3. Nuclear Structure and Reactions

3.1 Giant Resonances

Intermediate-energy proton and light-ion scattering is an ideal tool for studying one of the most foundamental characteristics of nuclear spectra - giant resonances (GR). It is surprising then that until recently relatively little input into this important subfield of nuclear physics had come from medium energy facilities. This situation is rapidly changing, however, as should be apparent in this talk.

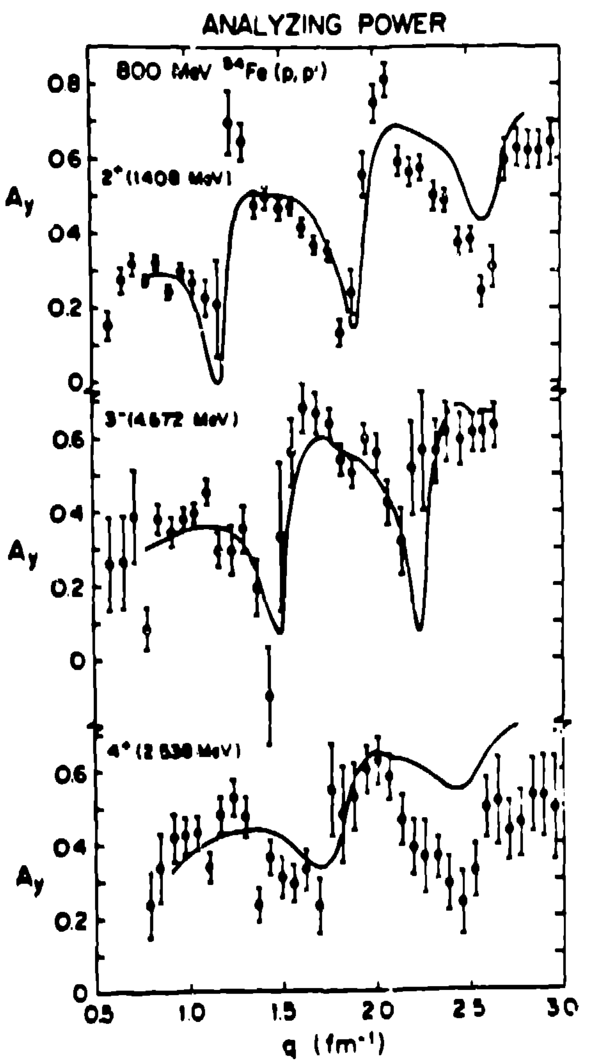
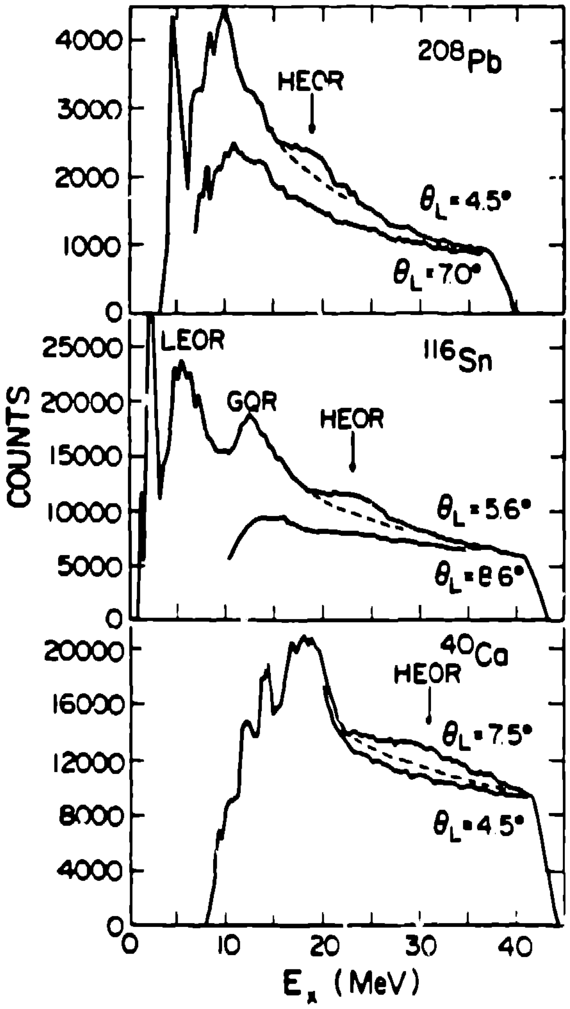


Fig. 3 Data-to-Data calculations of the analyzing powers of collective transitions.

The first observation of GR excitation at high-energy was made at Saclay where 1.37 GeV alpha particles were used to excite the giant quadrupole resonance (GQR) in ^{58}Ni.[13] It is encouraging to see this work continuing at Saclay with 480 MeV alphas.[14]

The first new GR observed at an intermediate-energy facility was the high-energy octupole giant resonance (HEOR) at $E_x \sim 110/A^{1/3}$ MeV, observed by our group at Los Alamos with 800 MeV proton scattering[15] (Fig. 4). This isoscalar resonance was predicted theoretically,[16] but not observed in numerous studies with 100 to 150 MeV alpha particles due to backgrounds arising from complex reaction processes (e.g. (^{4}He, ^{5}He*)) which obscure the high excitation energy region. High-energy protons appear to have the most favorable resonance-to-continuum background ratio yet observed in any GR experiment. This has allowed us to study the systematics (Fig. 5) of the HEOR over a wide range of A, including the relatively light nuclei ^{40}Ca and ^{58}Ni, where the resonance is 8 to 10 MeV wide.



Analysis of the strength of scalar-isoscalar GR's is commonly made in terms of the energy-weighted sum rule (EWSR)

$$\sum_n E_n\, B(E\ell)_n = \left(\frac{\hbar^2 A}{8\pi m}\right) \ell(2\ell+1) < r^{2\ell-2} >$$

which is a nearly model-independent quantity. Theoretical calculations indicate about 40 to 50% of the isoscalar E3 EWSR concentrated in the HEOR.[16] Our data show only 25 $\pm$ 10. Whether or not this is a real discrepancy depends critically on the assumption one makes about the continuum background. At present we use the standard and completely arbitrary procedure of drawing a reasonable line (dashed line in Fig. 4) and subtracting it from the data. It may soon be possible to improve on this method substantially. The continuum underlying GR's appears to be largely quasi-elastic scattering. Multiple-scattering theory calculations of this process[17] hold promise for a quantitative description of small q continuum spectra.

Fig. 4 Spectra from 800 MeV proton inelastic scattering showing the high-energy octupole giant resonance (HEOR). The lower spectrum for each target corresponds to a minimum in the octupole angular distribution.

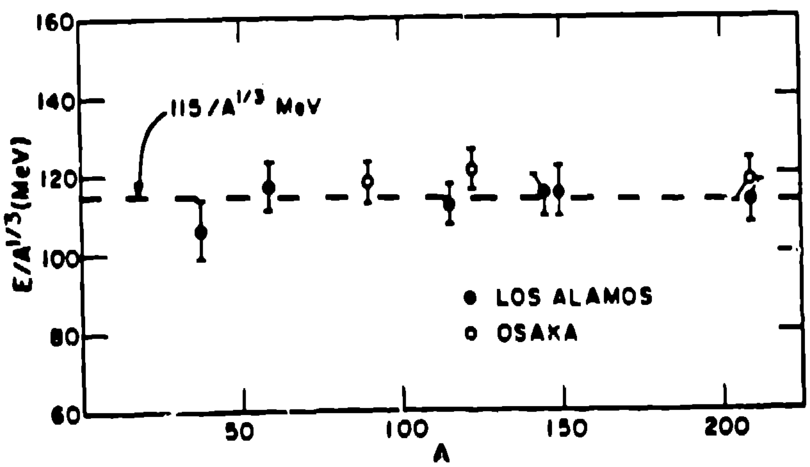


Fig. 5. Excitation energy systematics of the high energy octupole giant resonance.

With the discovery of the HEOR it is natural to ask, "are there GR's of higher multipolarity?" Our answer to this is a tentative, "no". In ^{115}Sn, the most completely studied case, we have taken very high statistics spectra in the region of the maximum for $\ell = 5$ and found only featureless continuum. Studies of $\ell = 4$ strength in the vicinity of the GQR[18] likewise indicate no great concentration of strength. Thus, at present, the possibility of finding well-defined GR's with $\ell>3$ seems remote.

To finish the discussion of GR's I want to briefly mention a new and very exciting discovery made at Orsay[19]. Figure 6 shows 200 MeV (p,p') spectra on the Zr isotopes at very small angles. The peak near E_x = 8 MeV has an angular

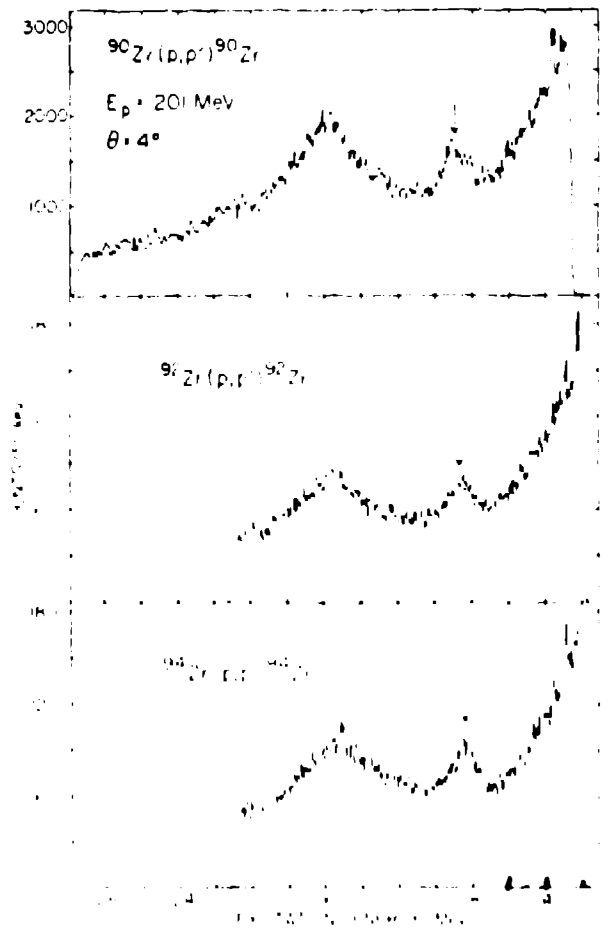


Fig. 6 Spectra from 200 MeV proton inelastic scattering showing the excitation of the M1 resonances (indicated by arrows).

distribution characteristic of $\ell = 0$. Since we know that the giant monopole resonance near $E_x \sim 16$ MeV contains most of the $\ell = 0$ ($\Delta s = 0$) strength, the most logical explanation is that the 8 MeV peak is the giant M1 resonance ($\Delta\ell = 0$, $\Delta s = 1$, $\Delta T = 1$). Its strength is about half of the single-particle sum rule, in rough agreement with the systematics of the Gamow Teller (GT) resonance.[20] The retardation of the strengths of the M1 and GT resonances has acquired increased significance as new theoretical evidence[21] suggests that admixtures of delta isobar-hole configurations may provide the answer.

3.2. PION - CONDENSATION PRECURSORS

A flurry of interest was generated about three years ago by the possibility[22] that normal nuclear matter might be sufficiently close to the critical density for pion condensation to show evidence of precritical behavior. Scattering of electrons and protons at momentum transfers of ~ 2 m_π to 3 m_π was suggested[22,23] as the most likely ground for observing possible precritical enhancements in the pion field of nuclei. Electrons, of course, offer the advantage of a well-known interaction. Their disadvantage is that they don't couple directly to pions, with the effect that (e,e') from a slab of near-critical nuclear matter would show no enhancement (for finite nuclei (e,e') may still probe the change in the pion field in the nuclear surface). Protons couple directly to pions but are, unfortunately, strongly interacting particles and therefore subject to another set of uncertainties.

Before describing the results of the experiments which are simple, I want to make a brief remark about the theories which are not simple. A crucial quantity in any calculation of pion condensation or precritical enhancement is the Landau-Migdal paramter g', which is a measure of the effect of short range correlations. When g' is assumed to be small (g' $\sim$ .3), the density for pion condensation is low, and predicted precritical enhancements are large. Conversely values of g' around 0.7 produce much higher critical densities and the corresponding enhancement in large q form factors is small.

A number of (p,p') experiments[24,25] with energies ranging from 122 to 800 MeV have searched for large q enhancements in the cross section of the 1^+, T = 1, 15.11 MeV state of ^{12}C. Figure 7 shows the combined data from two such experiments performed at Saturne and LAMPF. These experiments are probably

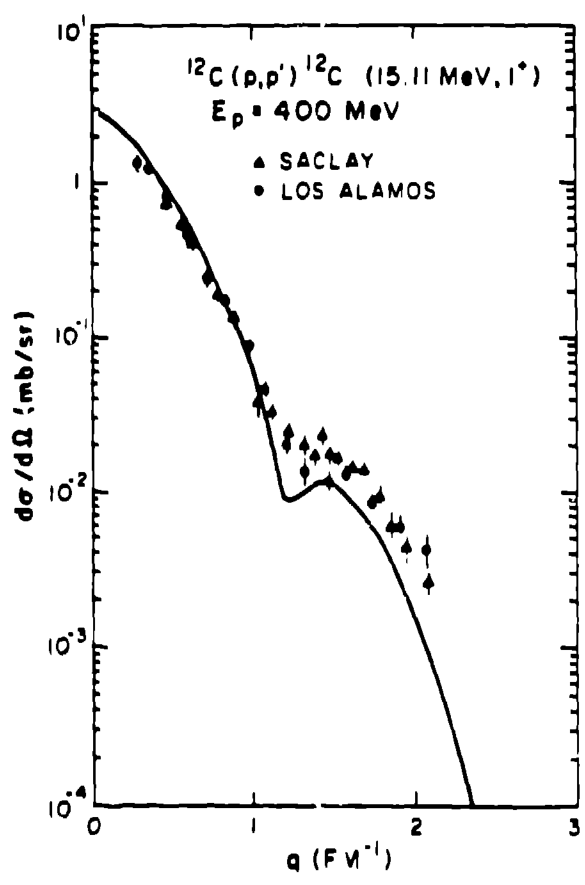


Fig. 7 Angular distribution for the excitation of the 15.11 MeV state in ^{12}C with 400 MeV protons. The curve is a DWIA calculation which is described in the text.

the best test of precritical enhancement thus far because the beam energy is high enough for the impulse approximation to be valid, and low enough so that the N-N interaction is known. The solid curve is a DWIA calculation by Love and Franey[26] using the Cohen-Kurath[27] wave functions. This calculation can safely be said to contain no precritical enhancement. An enhancement such as would result from a value of $g' \sim 0.5$ would raise the cross section in the q = 2 to 3 m_π region by perhaps a factor of 10. Although there is some discrepancy in the direction of precritical enhancement, several other non-exotic improvements in the nuclear wave functions need to be taken into account[28] before a quantitative analysis in terms of g' can be made.

The status of all present evidence, from (p,p'), (e,e'), and the analysis of unnatural parity states,[29] is that $g' > 0.65$ and does not strongly depend on q. Thus nuclei are not very close to the critical density for pion condensation and precritical enhancements are probably unobservably small.

3.3. New Polarization Experiments

3.3.1 General

One of the most attractive features of high-energy protons is that their long range makes possible the design of very efficient polarimeters. This has the consequence that the triple-scattering observables may be measured for nearly any reaction for which cross sections and analyzing powers can be measured. Two programs to exploit this new physics are underway, one using the QDDM spectrometer and a very simple focal-plane polarimeter for 150 to 200 MeV protons at the Indiana University Cyclotron Facility (IUCF),[30] and the other using a very extensive multi-wire chamber configuration (Fig. 8) in the focal plane of the high-resolution- spectrometer (HRS) at LAMPF. The latter utilizes the energy range 300 to 800 MeV. Initial work with the IUCF polarmeter is described in a contribution at this conference. I will briefly describe the experiments on the HRS polarimeter, which has been in operation for about 9 months (See the Contribution by J. F. Amman at this conference).

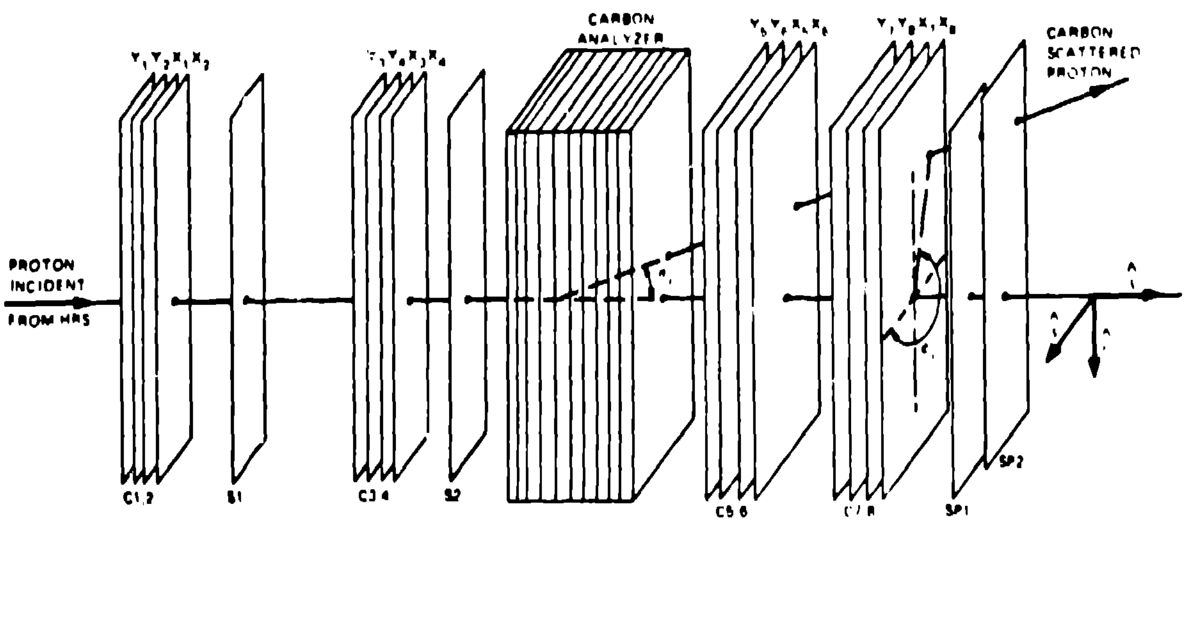


Fig. 8 Schematic representation of the HRS focal plane polarimeter. X and Y denote multiwire drift chambers with position sensitivity in the vertical and horizontal planes, respectively. S and SP denote scintillators.

The HRS polarimeter is an extremely versatile device which utilizes an array of multi-wire chambers to reconstruct the trajectory of protons scattered in a carbon block, as well as to perform the usual functions of determining the momenta and scattering angles from the primary scattering. The data acquisition system employs a fast microprocessor to reject events not scattered in the carbon block. Because of the orientation of the magnetic field of the HRS, the component of spin sideways and in the reaction plane (s) does not precess. The components normal (n) to the reaction plane and longitudinal (ℓ) precess by about 296 γ degrees (γ is the Lorentz factor) and are not measureable for certain values of the outgoing momentum. The polarization from the LAMPF accelerator may be adjusted to yield s, n, or ℓ initial polarization, thus any of the Wolfenstein triple scattering parameters[31] may be measured (with the exception mentioned above).

3.3.2. Measurement of Q for Elastic Scattering

The scattering amplitude for a spin 1/2 projectile on a spin zero nucleus can be expressed as

$$F(q) = g(q) + h(q)\ \sigma\cdot n$$

The usual cross section and analyzing powers give

$$d\sigma/d\Omega = |g|^2 + |h|^2$$

$$A(d\sigma/d\Omega) = 2\ \mathrm{Re}[gh^*]$$

By combining the triple scattering parameters, R and A, a new and complementary quantity Q can be constructed

$$Q(d\sigma/d\Omega) = 2\ \mathrm{Im}[gh^*]$$

The measurement of $d\sigma/d\Omega$, A, and Q results in a complete determination of F(q) apart from an overall phase.

The results of the first measurements of the Q parameter are shown together with the analyzing power (or polarization P for elastic scattering) in figure 9. This solid curve is a Glauber model calculation using the methods of Bleszynski and Osland[32] (The other curves are discussed in ref. 33). It is apparent that neither observable is quantitatively reproduced by the calculation in spite of the fact that at E_p = 500 MeV the N-N phase shifts are well known. Obviously future measurements of new observables such as Q will present new challenges to the theories of hadron-nucleus scattering.

3.3.3. Spin-Flip

The transverse spin-flip probability (SFP), S, is an observable which is closely connected to spin transfer (Δs = 1) in elastic or inelastic-scattering. In terms of the Wolfenstein parameter, D, S = 1/2 (1-D). In general it can be shown that S> 0.5 when Δs=1 dominates a reaction and S $\sim$ 0 when Δs = 0 is dominant.[34] The hope is that the SFP can be used as a signature of spin transfer processes in proton scattering and thereby probe such interesting nuclear structure phenomena as collective spin excitation and perhaps elucidate the validity of theoretical models of reactions where the tensor and spin-spin interactions are important.

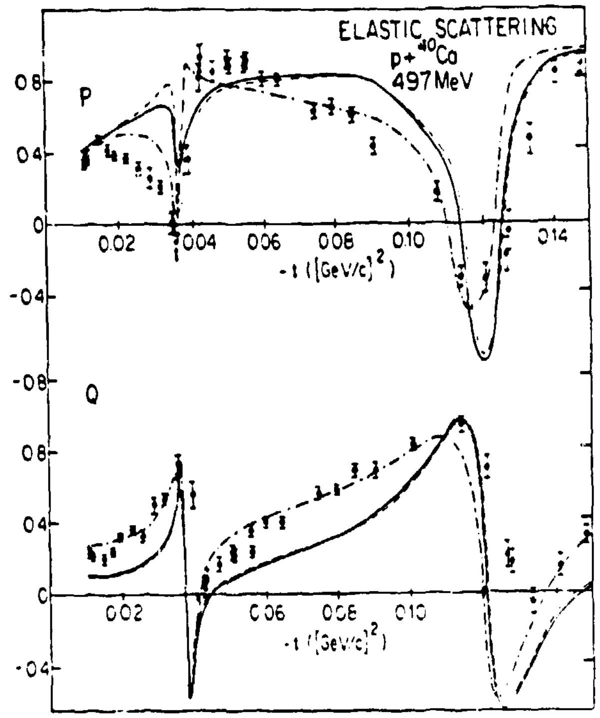


Fig. 9 Analyzing power and the Q parameter for elastic scattering from ^{40}Ca. The solid curve is a Glauber model calculation described in the text.

The latter objective is the primary aim in the first investigations (at LAMPF and IUCF) of the SFP at intermediate energies. Figure 10 shows the data for the two 1^+ states of ^{12}C excited by 400 MeV protons. Since $\Delta S=1$ excitation must occur if a single-step scattering dominates (an assumption which needs verification) one expects the SFP to be large. Quantitatively this is seen in the data and confirmed by DWIA calculations using the Love-Franey interaction and the Cohen-Kurath wave functions. Some divergence between theory and experiment is seen for the 15.11 MeV state at the larger momentum transfers. The reason(s) for this is (are) not known at present, nor does one understand why the SFP for the 1^+ T=0 state is reasonably well described by the DWIA whereas $d\sigma/d\Omega$ is not. The next couple of years should provide a much larger base of spin-flip and related experiments and eventually result in an increased understanding of the complex and rich physics of proton-nucleus scattering.

4. Conclusion

I hope that I have been able to convince you that high-energy proton light-ion scattering has recently made some very significant contributions to nuclear structure physics. Some of the areas touched on - giant resonances, possible evidence for delta isobar-hole configurations, and pion condensation precursors-have broad implications for many areas of nuclear physics. It should be obvious that new experimental methods (eg. polarimeters) combined with increasingly powerful theoretical techniques will make the next few years of high-energy proton and light-ion physics even more exciting.

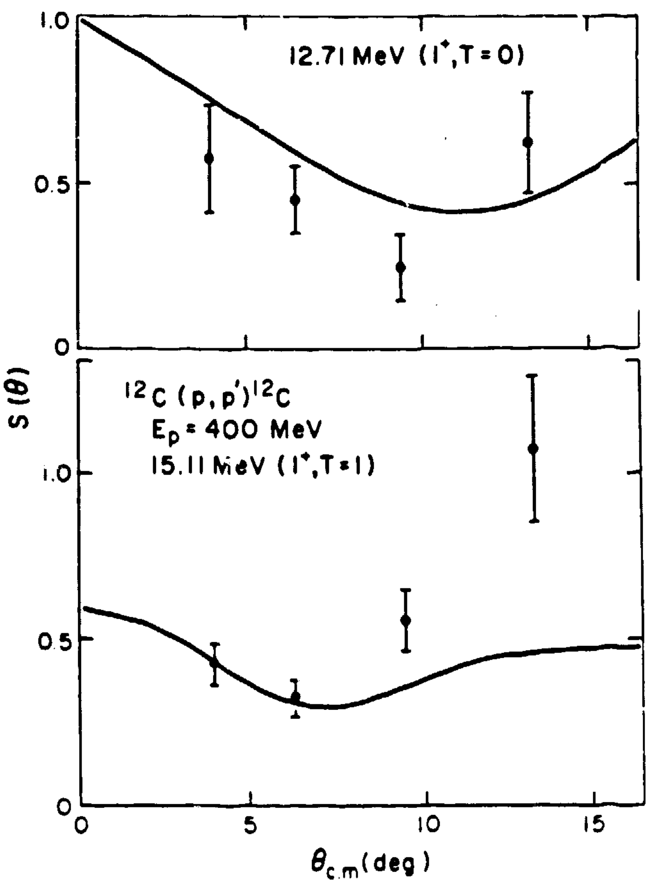


Fig. 10 Spin flip probabilities for the 1^+ states of ^{12}C with 400 MeV protons. The curves are DWIA calculations described in the text.

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